Permanent seismic monitoring in a remote location: Upgrades at Turtle Mountain

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INTRODUCTION

After a full year of operation, the surface seismic monitoring network at Turtle Mountain has experienced a mixture of successes and failures. We seek to share the experiences learned at Turtle Mountain.

Field Area

Turtle Mountain is where the infamous Frank Slide took place in 1903. This slide was one of the worst natural disasters in Canadian history, causing 73 deaths. The mountain is an unstable limestone anticlinal structure (Jones, 1993, AGS, 2003) with a number of large fractures at its summit. Prior to the slide, a portion of the near-vertical eastern limb of the anticline rested on clastic sediments and coal seams. It is widely believed that failure of this support caused the slide.

History

The current seismic monitoring system is the third of three seismic monitoring efforts at Turtle Mountain. In 1981 the Pacific Geoscience Centre installed a seismometer at the base of Turtle Mountain. This single-station system indicated the presence of local seismic activity. It was not until the second seismic monitoring system was installed by Alberta Environment that more became known about local seismic activity. The second system operated from 1986 through 1996 and produced a dataset of over a hundred local seismic events in and around the mountain. Only recently has this dataset been interpreted (Chen et. al, this volume). A need for continued monitoring of Turtle Mountain was recognized by the Alberta government in 2003, and a project was launched to re-instrument the mountain under the department of Emergency Management Alberta. This project installed a network of surface-seismic monitoring stations on the mountain. An existing surface seismic monitoring station, installed by staff from the University of Calgary, was incorporated into the network. Upon completion of the project, control of the system was transferred to the Alberta Geological Survey (AGS). AGS continues to operate the seismic array and works to improve and expand its monitoring capabilities through a maintenance and development program.

System description

The surface seismic monitoring system is comprised of six stations located on the north side of Turtle Mountain (Bland et al., 2004). Each station is equipped with a four-channel seismic digitizer connected to a radio for wireless network data transmission. The electronic equipment and solar power generating panel are mounted on a 2 m mast. At present, most of the stations have three channels connected to the X, Y, and Z axes of a 3-component geophone string (one channel is spare). The geophone strings are comprised of three discrete 3-C geophones which are planted within close proximity to each other (<1 m). The geophones contain OYO Geospace GS-20DM elements which have a natural frequency of 28 Hz.

A borehole was drilled at the top of Turtle Mountain near South Peak. It was instrumented with two levels of 3-C geophone sondes manufactured by Terrascience Ltd. A Terrascience Microseismic Acquisition system digitizes the borehole signals and data from both surface and borehole systems are combined for analysis.

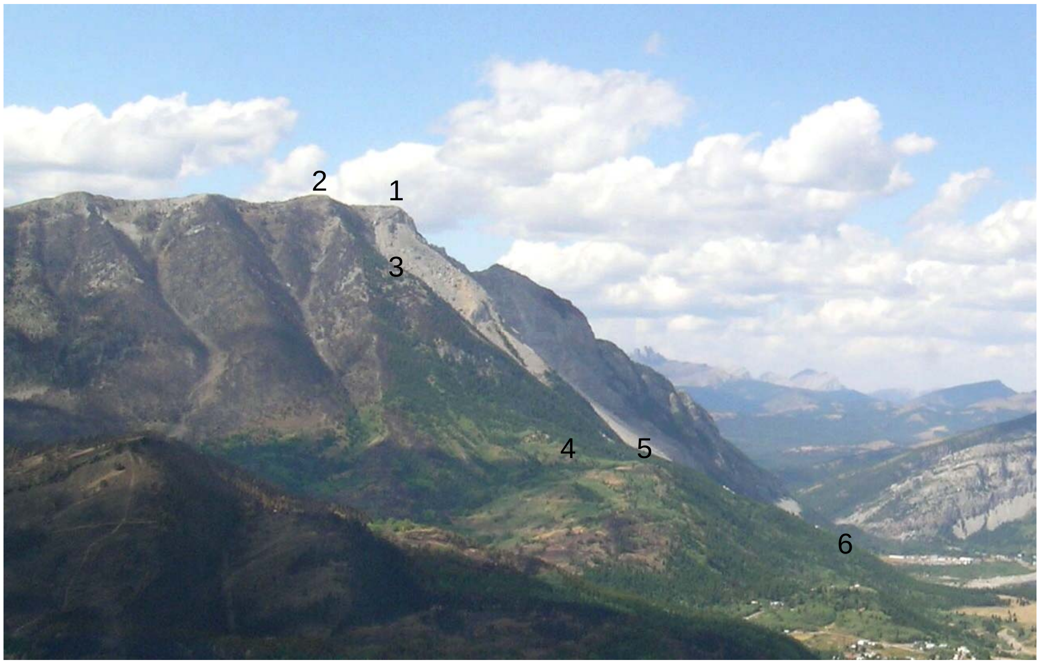


Figure 1. Turtle Mountain surface seismic station locations. The stations are (1) South Peak, (2) Third Peak, (3) Ridge, (4) Relay, (5) Pit and (6) River. The borehole station is just out of view near South Peak station.

SYSTEM RELIABILITY

The stations, which make-up the present-day seismic network were installed in the winter of 2003-2004 by Gennix Technology Corp. Overall the stations have been largely operational, and have produced a rich dataset of seismic activity.

Figure 2 shows the operational status of each of the stations since they were activated in April 2004. Once can clearly see that the most problematic station has been the one at South Peak. Maintenance of the two mountain-top stations requires a two hour ascent (by foot) or use of a helicopter. Maintenance trips to South peak, Third peak and Ridge stations require more planning and are more expensive than trips to the lower stations. As a result, downtime at these stations is typically longer than at the lower stations.

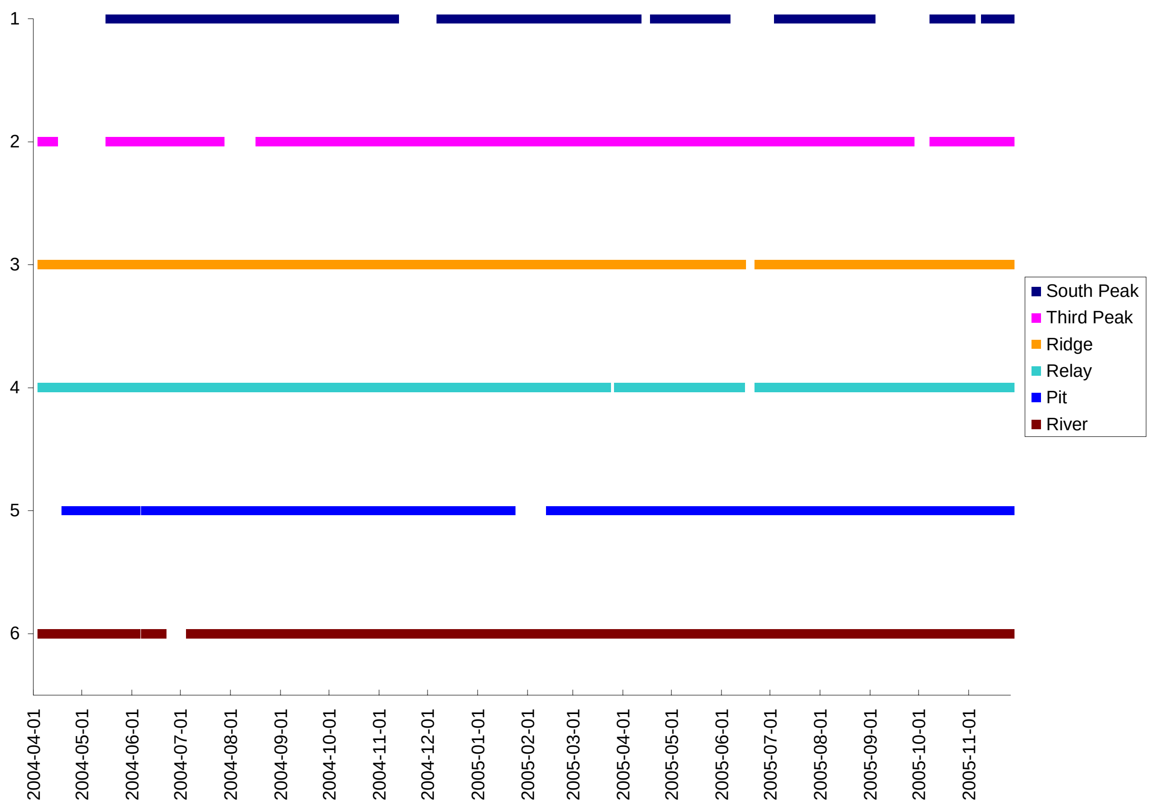


Figure 2. Surface seismic system uptime since installation. The presence of a bar indicates system operation. The time scale, indicated as year-month-day, appears on the horizontal axis.

Geophones

The 3-C geophones and their associated cables have operated flawlessly to date. The geophones are periodically tested by applying a calibration pulse. This is done remotely via a test feature built into the seismic digitizers. The geophone-element impulse response is analysed, and from this, we can confirm that electrical connectivity is good, and that the elements respond with the expected natural frequency and damping factor. Geophone cables (30 m of cable at each station) are protected from abrasion, UV breakdown, and animal damage by "liquid tight" flexible conduit. So far, there have been no issues with the elements or the geophone cables.

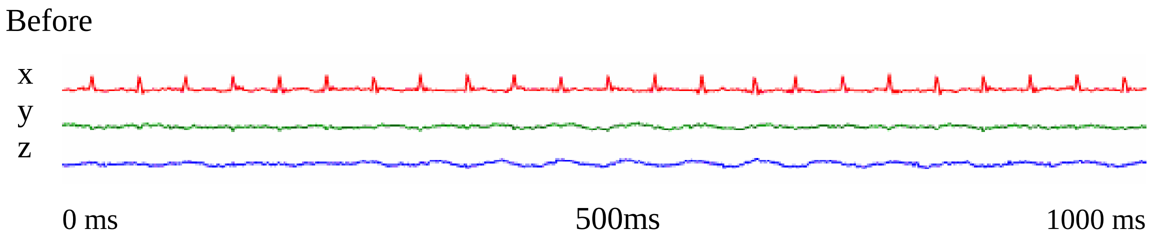
The geophones were planted by drilling a hole in the rock to accept the geophone spike. After forcing the spike into the hole, the geophone was oriented and covered in plaster of Paris. After the first year of operation, the plaster is heavily weathered at many of the sites (Figure 3). At some sites, the plaster appears to have detached from the underlying rock, so it does little to improve coupling. In future, the geophones will be re-secured using cement.

Figure 3. The northern-most geophone on South Peak is photographed on its installation date (left) and 5 months later (right). The plaster shows signs of deterioration.

Digitizers

The seismic data are acquired by four-channel digitizers located at each station. These digitizers do not have any internal storage – all data are transmitted via a wireless network to a control centre at the base of the mountain. There, data are stored on computer hard drives for further analysis.

The digitizer system was a new design, and many of the early development issues were resolved in the first few months of operation. One serious issue with the digitizer was its susceptibility to radio frequency interference. When the digitizer was operated in close proximity to the data transmission radio, vestiges of radio signals would leak onto the seismic data. This interference was not noticeable during bench tests in the laboratory, but once the system was installed on the mountain the radio noise became the dominant source of background noise. The source of the noise was tracked to a preamplifier which was susceptible to RF pick-up. Replacement of the preamplifier circuitry on the A/D converter board solved the radio pickup problem. In the spring of 2005 all the A/D circuit boards were replaced by new ones featuring the new preamplifier. The resulting noise reduction is illustrated in Figure 4.



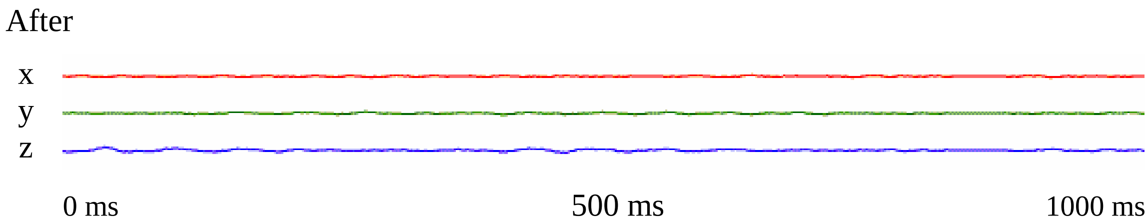


Figure 4. Data from the older A/D converter board in the surface seismic systems introduced radio noise (top). In this example, spikes are most visible on the X-component. Output from the new A/D converter boards (bottom) no longer contains the 40 Hz pulse train.

Another early issue with the digitizer was its radio-fault recovery system. In 2003, the most common wireless network radio was the Linksys WET11. It had been used by another seismic acquisition group with mixed results. Based on their trouble with radio lock-ups, we added a radio power-cycle feature to the digitizers. This feature allowed any attached radio to be power-cycled if there was a loss in connectivity with the monitoring control centre. This fault-recovery system turned out to reduce the reliability of the system rather than contribute to it. At low temperatures, the start-up current draw of the radio was significantly higher than expected and the power transistor used for the power switching would fail during the power-up operation. To solve the problem, the transistor was replaced with one having an order of magnitude more power handling capacity. Curiously, one of the few instances when the recovery mode was activated was when a downed power line cut power to the monitoring control centre. In this case, power cycling the radios had no effect in re-establishing connectivity to the control centre. Within ten minutes, the seismic digitizers faithfully executed their failure-recovery circuit to power cycle the radio. Unfortunately, this operation caused the switching transistor to burn out at two stations, making them permanently lose contact. A service mission was required to replace the transistors and re-establish connectivity.

At present, the fault recovery circuit (with the upgraded transistor) is still enabled. To reduce the chance of failure due to unnecessary power cycling, the digitizer's software has been modified so that the failure-recovery mode only takes effect after several hours of lost contact.

Radios

Wireless network radios are used to transmit data from the seismic digitizers to the control centre at the Frank Slide Interpretive Centre. We have had many problems with the network radios, particularly at the South Peak monitoring site. In most cases, radio failures are attributable to lighting activity on and around Turtle Mountain. When the system was first installed, consumer-grade "wireless client bridge" radios were installed at each station (Engenius model NL-2611CB3 PLUS). After two radio failures at South Peak, the radio was replaced with an industrial grade, outdoor radio (a SmartBridges Airbridge Outdoor). In spite of this upgrade, radio failures continued at South Peak. It would seem that this site is particularly vulnerable to radio failure, possibly due to lightning and static discharge occurring near the peak. There are no outward signs that the station's mast has received a direct hit; however, component failures on the seismic digitizers indicate that large surge currents have flowed through various electrical components in the station.

Lightning damage can be mitigated in three ways: 1) Using lightning surge-arrest devices, 2) providing good equipment grounding, and 3) through the use of grounded lightning rods. Lightning surge protection has been strengthened at South Peak by the addition of differential gas discharge tubes on the geophone inputs. A new grounding plate has been added to South Peak to help provide a more conductive path to ground. Before the next lightning season, we propose the installation of lightning rods on the mountain-top masts to provide even better protection to the installed electronics. Even with all these protective measures, the power of a direct lightning strike is tremendously difficult to combat. We believe that at the peaks of Turtle Mountain, lightning will continue to threaten electronic equipment each summer, and complete protection may not be possible. Though the risk of damage can be mitigated using standard lightning protection strategies, the addition of more stations would provide redundancy which could lead to a more reliable network overall.

The wireless network was designed to handle data traffic for the surface seismic monitoring system only. The addition of a borehole seismic recorder operating at higher sample rates created capacity difficulties for the surface seismic data network. Even though the network is based on IEEE 802.11b technology, which supports signal rates up to 11 Mbits/s, the wireless network is unable to achieve this transfer rate continuously. In order to overcome the poor signal-to-noise ratio associated with operating over great distances, the transmission rate is reduced to 1, 2 or 5 Mbits/s (depending on distance). The IEEE 802.11b protocol works best when stations are able to detect when the radio channel is in use. Ideally, radios listen for breaks in transmissions before transmitting their own data. On Turtle Mountain, radios are fitted with high-gain directional antennas which point at the Control Centre at the Frank Slide Interpretive Centre. Station radios are unable to detect when other radios on the mountain are transmitting, so a novel method was devised to prevent collisions; each station is given a GPS clock synchronized time-slot, during which it transmits its digitized time-stamped data. Forty times per second, each station, in turn, transmits data to the control centre at the base of the mountain. The borehole seismic recorder was not programmed using the same communications protocol, and so it did not participate in the choreographed data exchange. Its presence seriously degraded the wireless network's ability to send real time data without gaps.

Early attempts to solve the network capacity problem involved adding a second wireless network based at the same control centre. The idea was that if transmissions to South Peak operated on a separate frequency channel, there would be no interference between the two systems. Indeed this helped significantly, but the new radio channel still did not perform quickly enough to support the additional data load of the high-speed borehole acquisition system.

In the fall of 2005, a new high-speed radio link was established to South Peak operating at 5.8 GHz using IEEE 802.11a technology. The radio system, implemented using a pair of SmartBridges AirHaul Nexus radios, provides a much faster data link. Early testing shows that sustained transmission rates of 13 Mbits/s are possible. The new bandwidth has allowed us to increase the borehole recorder's sample rate to 2000 kHz, and ample bandwidth is still available for the addition of new data collection equipment.

Figure 5. New antennas for the link between the Control Centre at the Frank Slide Interpretive Centre (left) and South Peak station (right).

Solar power systems

All monitoring equipment at Turtle Mountain operates using solar power. Most of the monitoring sites were selected so that they would receive sunlight year-round. Two sites were selected for their geological significance, rather than their suitability for solar power. River station is located near the entrance to a (now abandoned) coal mine at Turtle Mountain. This station provides critical spatial coverage of the north side of the mountain. As winter approaches, the station receives very little sunlight because the mountain casts a shadow over the area. Pit station is located near the site of a major subsidence pit caused by the collapse of mining tunnels. This site is also shaded for portions of the winter.

During the first winter of operation, both River and Pit stations had difficulties generating enough solar power to operate their monitoring electronics. The River station had been fitted with a wind generator to provide additional generating capacity, but the generator suffered broken blades after being buffeted by the strong winds. Maintenance of the wind generator, located at the end of a 24-foot mast, was difficult and dangerous in the uneven terrain of Turtle Mountain. The generator's propensity to fall was also considered a public safety concern. We decided to uninstall the wind generator and replace it with additional solar generation capacity and additional batteries. In addition we moved the solar panels to a site which is free of tree cover. Additional solar panels and batteries were also installed at the Pit station. Now, both stations have double the generating capacity and have over 800 Ahr of battery storage. This should help maintain operations for extended periods without direct sunlight.

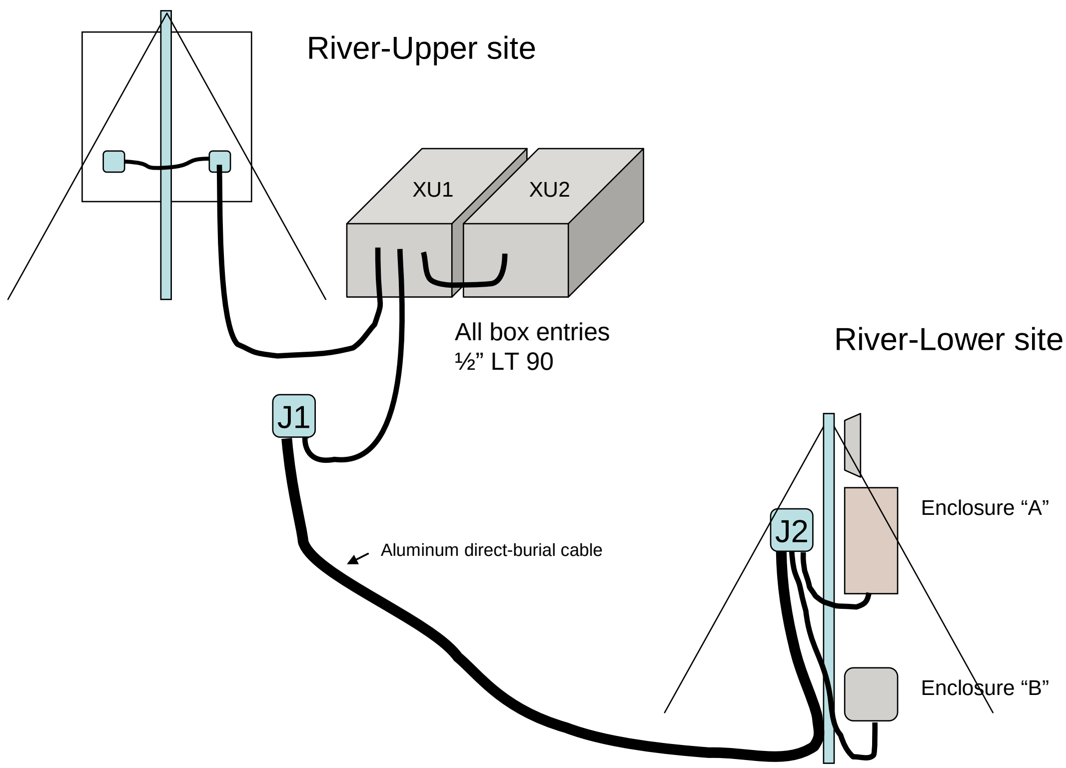


Figure 6. Equipment layout diagram for the River station after upgrades performed in 2005. Solar generation was moved upslope to a new site which is free of trees. The new "River-Upper" site is connected to the original "River-Lower" site using a 100 m long Aluminum power cable formerly in use for the wind turbine. Electronics for the surface seismic geophones and stream-flow monitoring system remain at the lower site.

Figure 7. Upgraded power generation system at Pit station. The upgraded system (right) now provides double the generating and storage capacity.

Data acquisition and processing computers

Data acquired at Turtle Mountain is collected by software at the Monitoring Control Centre at Frank Slide Interpretive Centre. Three different computers had been used there in association with the passive seismic monitoring effort – one computer to marshall the data from the surface recorders, one computer to perform data analysis, and one computer to store seismic and other data in a database. Among all three computers there are six hard drives. After one year of operation, three hard drives failed. In the case of the database server, the RAID-5 storage system mitigated the effect of the hard drive failures, and no downtime or data loss occurred. In the case of the failure of the Marshall computer's hard drive, the system failed and the surface seismic system became inoperative as a whole. In order to affect a quick repair, we combined the marshalling operations with the seismic data analysis on a single computer. A few changes to the marshalling source code, written in Java, allowed us to move the program from a Linux machine to a Windows machine. This change reduced the number of computers and operating systems to maintain, and has improved the overall reliability of the system.

Data acquisition software

Data from the six surface seismic stations and the two-level borehole system are combined into an integrated data stream. A program from Terrascience Systems Ltd. called AutoTAR® performs event detection and data transcription. This data stream contains seismic events analyzed using the short term average over long term average (STA/LTA) event detection technique. This technique generally works very well: When the STA/LTA ratio exceeds a pre-defined threshold, a channel is said to have "triggered". The acquisition software adds an additional layer of logic prior to storing data to disk. It only stores events if multiple, coincident triggers occur on a multiplicity of channels or stations. The minimum number of channels and the minimum number of stations is adjustable.

One of the challenges of operating the system has been the selection of the triggering parameters. Triggering may be adjusted on a station-by-station basis, with the ability to perform adjustable band-pass filtering ahead of the event detection. Selection of the trigger parameters impacts the sensitivity of the system; both to bona fide seismicity and to noise. Incorrect adjustment of the trigger parameters leads to an unmanageable number of event files. To add a further complication, geophones are also subject to wind and precipitation noise. Rainstorms generate constant impulses on the geophones which, in turn, cause the triggering system to generate an excessive number of event files. Due to the uncommon nature of this installation, a large amount of effort has gone into the adjustment of trigger parameters so that an optimal number of events are collected and no high-quality events are missed. Looking forward, we hope to implement some changes to the event detection algorithms which will make them more robust. Specifically, we want to add code which makes the system less prone to recording raindrop hits as seismic events.

Line Power

The systems in the Turtle Mountain Control Centre, located at the Frank Slide Interpretive Centre, are protected by small, consumer-grade, uninterruptible power supplies (UPS). There have been about four power failures in the two years that the systems have been operating. Two failures were brief, and were handled by the UPS systems. Two failures were of an extended nature (one lasting 5 hours, one lasting several days). The UPS systems were unable to cope with the long outages, and seismic monitoring was inoperative for these periods. Implementing a UPS system which handles multi-day outages is extremely costly, and one must consider whether the investment is worthwhile – particularly if other components of the monitoring system are significantly less reliable. In order to increase overall system reliability, one needs to carefully study the failure probabilities of all systems, and direct efforts into those areas with the highest probability of failure (usually by adding redundancy). Considering overall power-related downtime, the control centre power is remarkably reliable.

System Upgrades

Geophones

When the surface seismic monitoring system was installed, a string of 3-component geophones was installed at each of the sites (Figure 8). Three component geophones are able to record more information than their single component counterparts. With three-component geophones one can measure the 3-dimensional direction of first motion or separate *P*- and *S*-wave arrivals using polarization filtering techniques. On Turtle Mountain we have had limited success with either of these analysis techniques. Rather than see clearly defined *P*- and *S*-wave arrivals (as one might expect to see in a borehole geophone installation), we see highly disorganized and chaotic waveforms at the surface. We believe this may be due to multi-pathing as a result of a severely fractured subsurface.

Figure 8. Three-component geophones are installed on Turtle Mountain (2003).

In the fall of 2005, an experimental micro-array was deployed at South Peak. The micro-array consists of four conventional vertical component geophones arranged in a star configuration about the mast. The primary motivation for testing the new micro-array was to see if we could improve the sensitivity of the system to nearby events (<500m range), while rejecting nuisance event triggers caused by wind, windborne snow and pebbles, and precipitation. By replacing the 3-component geophone with a set of four spatially-separated geophones, we reduce the likelihood of nuisance triggers occurring coincidentally on all channels of one station. The acquisition software (AutoTAR®), allows one to adjust the system's triggering criteria so that only microseisms causing multiple, coincident triggers are recorded to disk. This simple event filtering technique greatly improves the ratio of "good" events (those recording bona fide microseismicity) to "noise" events. It permits us to reduce the amplitude threshold for triggering without an unmanageable increase in recorded noise events, thereby increasing overall sensitivity.

Data from the existing 6-station array has been used for hypocentre location studies, but the small number of recording sites makes it difficult to obtain robust hypocentre solutions. The recording stations are widely spaced and many events are not powerful enough to be recorded on more than one or two stations. Increasing the number of geophone sites greatly facilitates hypocentre location. With four spatially-separated channels per micro-array, we will have the ability to perform arrival-time based hypocentre analysis using data recorded by a single station.

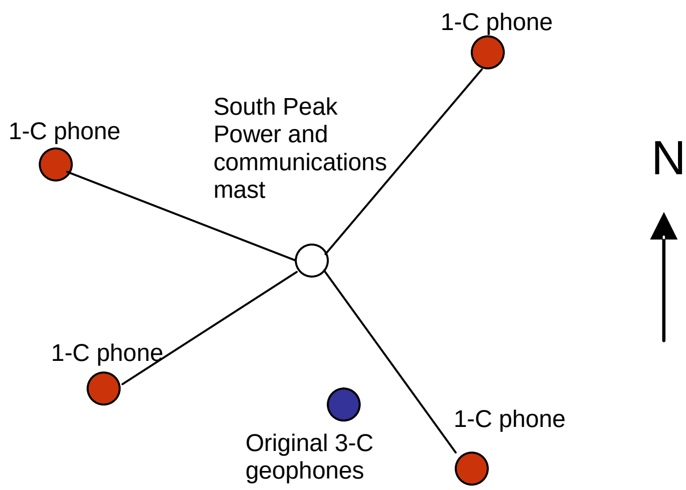


Figure 9. Map showing the approximate location of the new South Peak geophones relative to the South Peak mast.

Figure 10. Location of South Peak micro-array geophones.

The new geophones differ from the original geophones in the following aspects:

Table 1. Differences between original and new geophones at South Peak.

Attribute	**Original**	**New**
Number of components	3 (x, y, z)	1 (z only)
Number of elements summed per channel	3	1
Geophone sensitivity	0.384 V/in/s	0.81 V/in/s
Natural frequency	28 Hz	4.5 Hz
Potting compound	Plaster of Paris	Concrete
Depth of potting	1-5 cm	10 cm

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Figure 11. The new geophones are encapsulated by a concrete cylinder. A rock is used to hold the forms in place while the cement cures.

Only a few seismic records from the new South Peak micro-array were available at the time of publication. Some example seismic records from the array are shown later in this report. We will not be able to use this data for hypocentre location until the geographic locations of the geophones are surveyed (scheduled for December 2005). Early data show that the new geophones produce greater output than the previous geophones. We are also able to see move-out across the spread. This is encouraging, as it means that the new micro-array should yield valuable data for hypocentre location.

DATA

The microseismic monitoring system has operated since March 2004. In that time, over fifty thousand microseismic events have been captured.

Frequency content

During the design phase of the system, tests were performed on limestone outcrop at the base of the mountain to estimate seismic velocity and get a sense of the expected frequency content of data. Based on these tests, we expected to see data with frequencies in the 100-150 Hz range. Although we see these kinds of high-frequency events at individual stations (Figure 12), we find that sizable events, those detectable at multiple stations, are significantly lower in their frequency content. There has only been one observed case where high-frequency events were detected at multiple stations (Figure 13). In this case, it is doubtful that a single event is responsible for the observed seismicity. The arrival time differences do not make sense considering the geometry and nominal seismic velocity (4.5 km/s).

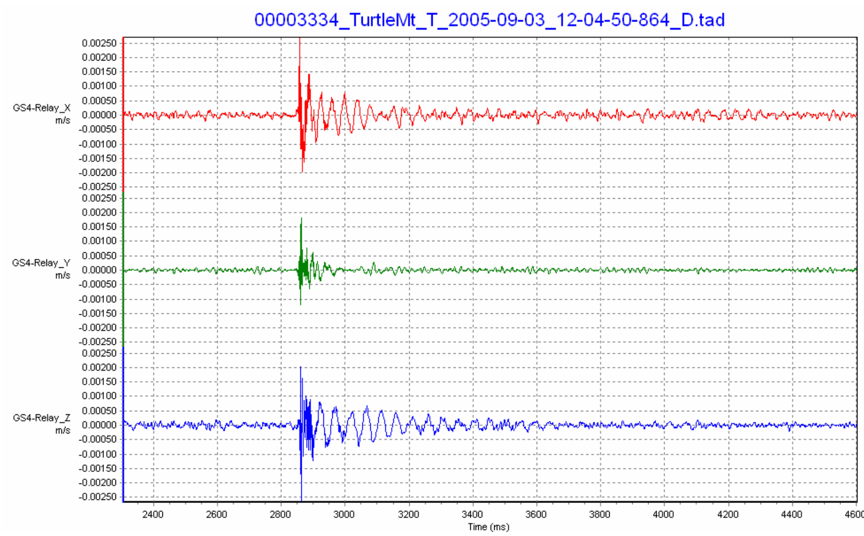

Figure 12. An example of a high-frequency microseismic event detected at a single station. Events with high frequency content are limited to single-station pick-up.

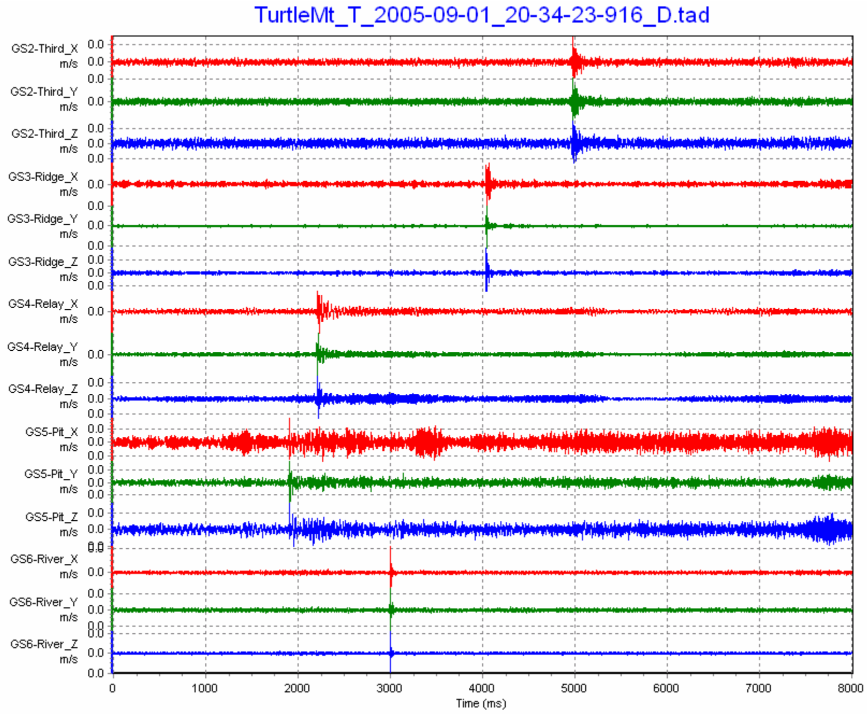

Figure 13. A rare case where high frequency events are detected at multiple surface seismic stations. The broad range of arrival-times suggests that the observed seismicity is the result of multiple source events.

Events which register at multiple stations typically contain much lower frequency content. We analyse the power spectral density (PSD) of the event shown in Figure 14 using Welch's averaged modified periodogram method of spectral estimation (Matlab, 2005). The PSD for each arrival at Ridge station is shown in Figure 15. We see that most of the energy is in the 15-40 Hz band, with the peak at ~18 Hz.

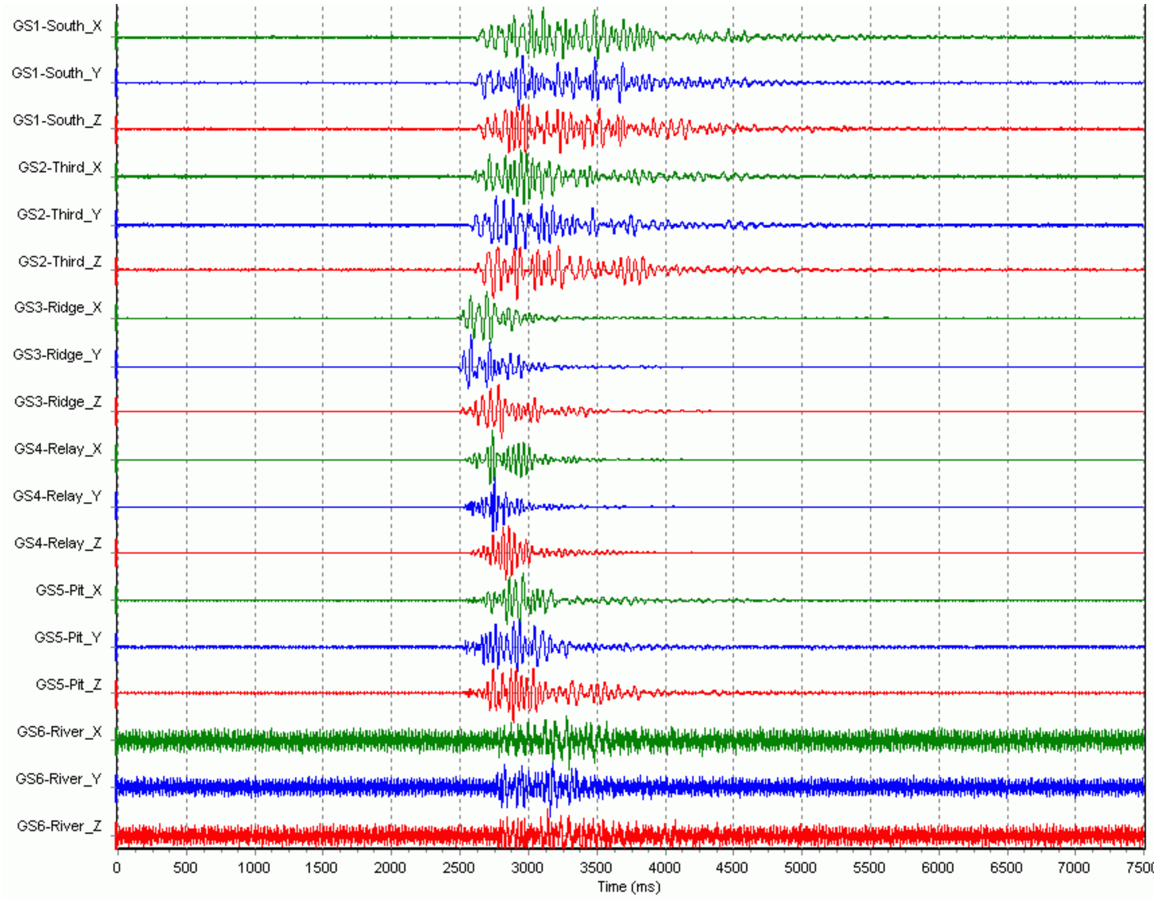

Figure 14. Seismic event detected by the surface seismic array. Traces have had amplitude scaling applied to normalize the peak value.

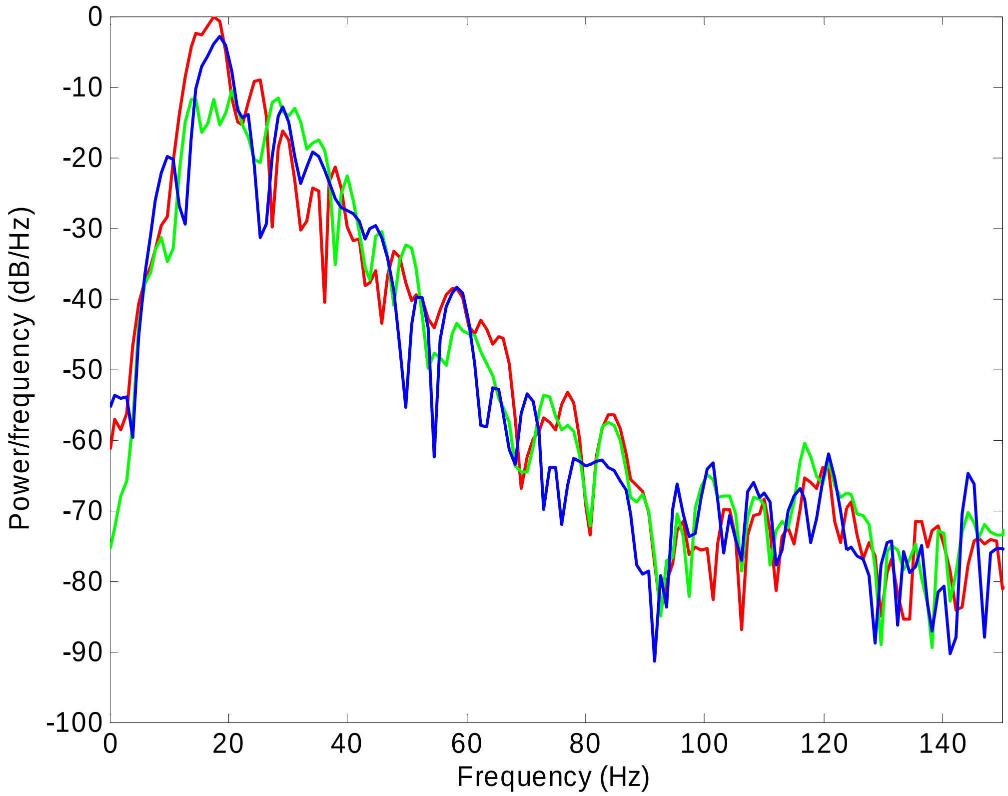

Figure 15. Power spectral density of the microseism of Figure 14 as received at Ridge station (the station nearest the event). The x-component (red), y-component (green) and z-component (blue) are plotted relative to the combined maximum for all three components.

Observed Seismicity

The seismic monitoring system records hundreds of event files each month. These events can be grouped into the following classes

- High quality events with distinct, sharp arrivals detected at multiple stations
- Single-station high-frequency events with distinct *P*- and *S*- arrivals visible
- Low quality events which have less distinct (emergent) first arrivals.
- Multiple-source events, most likely caused by rock slides (Figure 16)
- Environmental noise (wind, tree branches, wildlife, humans)
- Electrical noise (charge controller switching)
- Regional events associated with nearby mine blasting operations (Figure 17)
- Teleseismic events
- Train whistles
- Precipitation (rain or snow hitting the surface geophones)

Of these event types, only the first four are of interest when trying to understand the geomorphology of Turtle Mountain. By far, the most useful data are those indicating clear *P*- and *S*-wave arrivals. We have thus far seen few high quality events with pickable *S*-wave arrivals. Figure 18 is a rare exception. To date, most hypocenter analysis has been performed using *P*- arrival times only.

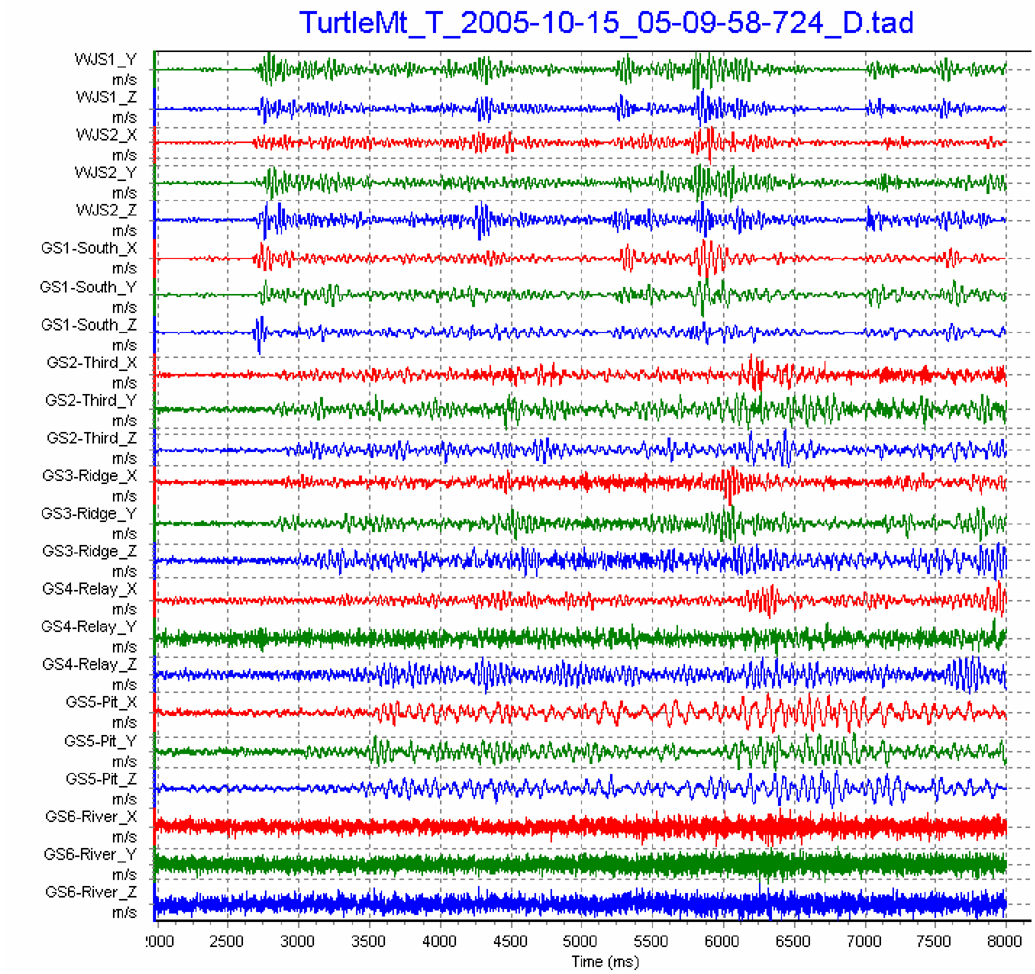

Figure 16. This multiple-event record could be the result of a rock slide or swarm of microseisms.

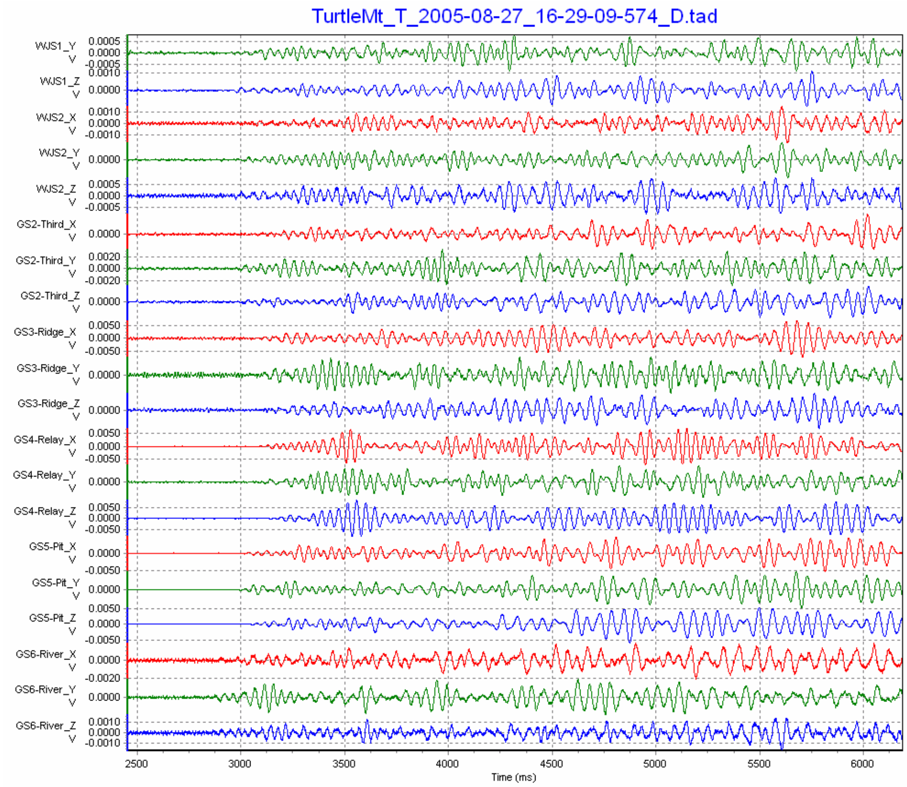

Figure 17. A seismic event probably caused by nearby mine blasting. Typical characteristics of these events are: (1) low frequency content, (2) first arrivals at stations low on the mountain and (3) event durations of more than 5 seconds.

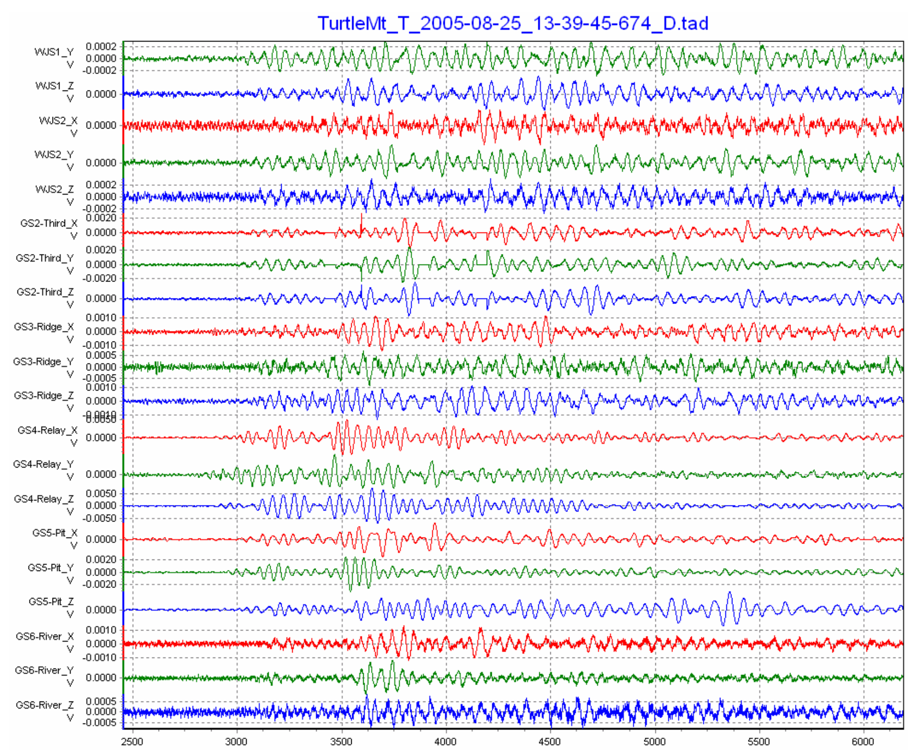

Figure 18. Large seismic event originating in the vicinity of Relay station.

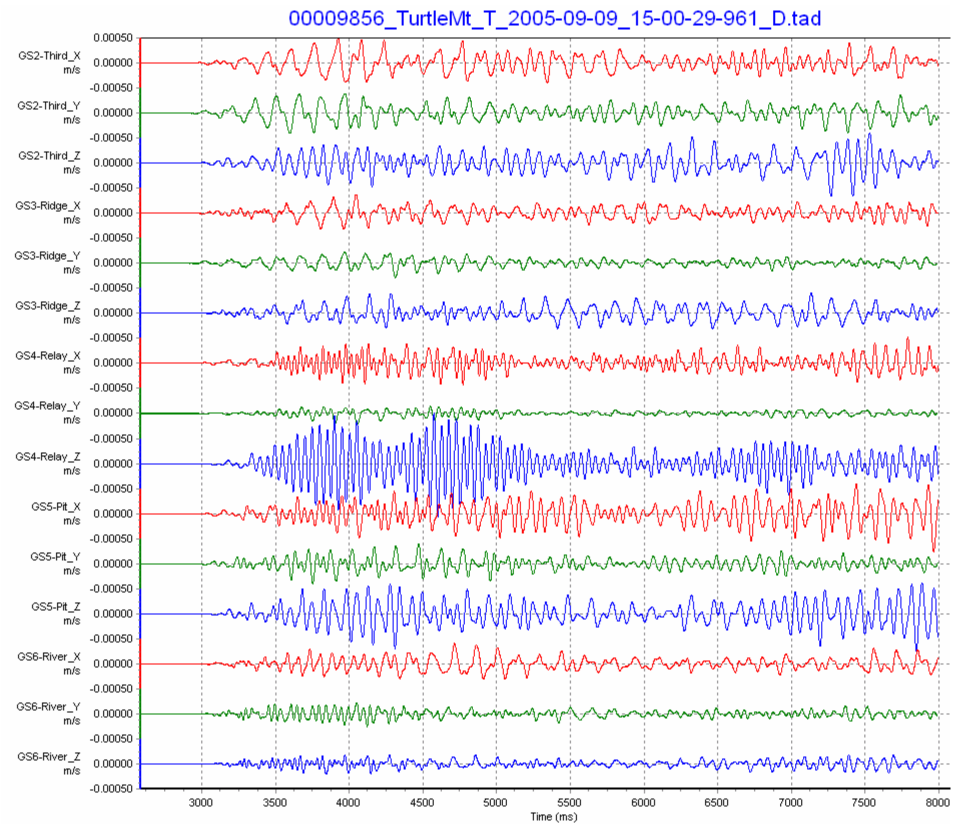

Figure 19. This event (September 9th, 2005) was exceptionally large. The peak amplitude recorded at Relay station was 1 mm/s.

DISCUSSION

Installing and maintaining a continuous-recording seismic system on mountainous terrain has made equipment reliability a major concern. The time and cost involved in fixing even the slightest problem is multiplied by the difficulty of reaching the site, particularly during Canadian winters. Compounding this problem is the fact that many subsystem failures can cause the same problem (i.e. loss of radio contact), so that it may be fundamentally impossible to know what spare parts are required before arriving on site. Based on this experience, we recommend that future remote monitoring systems place a high value on system redundancy. Adding spare stations to a monitoring network has a high initial cost, but the reduction in urgent maintenance trips makes this a worthwhile consideration, particularly when large amounts of time are required to reach the site and perform any repairs.

Another important effect on reliability is system simplicity. We find that those stations which are simplest are much more reliable than those which have been adapted to work with non-surface-seismic systems. On Turtle Mountain, two stations carry non-surface-seismic data. South Peak station was adapted to carry the seismic data from the borehole seismic system, and River station transmits data from stream-flow monitoring equipment. Both these sites have had reliability issues associated with their modification. Whenever feasible, it is best to keep all stations the same. If additional capabilities are required, there is a distinct reliability advantage associated with adding whole new installations (complete with solar panels, batteries, and radios). By avoiding equipment interdependencies, systems have better overall reliability.

We have learned a great deal about remote seismic monitoring since we first designed and installed the system. Turtle Mountain has proven to be a highly challenging site in which to remotely operate a seismic monitoring network. Its successful operation is the result of a strong commitment by all those who designed, installed, managed, and funded the project.

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